ARKIV FÖR FYSIK Band 11 nr 43

Communicated 28 November 1956 by George de Hevesy and Harald Norinder

Conduction of electricity through ice and snow

I. Discharge of a condenser through ice crystals

By Reinhards Siksna

With 17 figures in the text

1. Introduction

Different phenomena related to the problem of electrification of snow and ice have been the subject of the investigation carried out at this institute for some time [17, 18, 19]. The diversity of the phenomena observed led us to the idea that the elementary electric properties of ice and snow must be investigated in greater detail for gaining a secure basis for further speculation and investigation.

Concerning these elementary electric properties it should be noted here that because of the polar effects in ice enough work has been devoted to the investigation of its dielectric properties, including examination of the variation of the dielectric constant with variation of the frequency applied. A comparatively complete survey of this subject is given by Humbel, Jona and Scherrer [9]. Some additional contributions to the same problem have been made by Gränicher, Jaccard, Scherrer and Steinemann [7, 8].

Too little attention is paid to the electrical resistivity or conduction of electricity through ice and snow. The electrical resistivity of ice has first been measured by Ayrton and Perry [2]. A more systematical work has been done by Johnstone [10], but it is evident that another approach to the problem must be undertaken now. A contribution of Brommel [5] must be mentioned next. Very high resistance of ice is noted at a temperature of −80°C by Bandel [3] in his work about corona from an ice-point. It may be noted here that the investigation of the resistivity of ice in dependence on the temperature below −70°C might be of particular interest because diamond structure has been stated for ice at such a low temperature by Koenig [12, 13]. New evidence concerning this question has been produced by Lisgarten and Blackman [16].

In addition to these contributions on the resistivity of ice, there are our preliminary measurements carried out only for orientation [18]. This is all what is known on the subject under consideration.

By setting up the task for the present investigation of the electrical resistivity of ice the following circumstances were taken into account.

As shown by our experiments [17, 18, 19], nearly all electrical phenomena related to snow and ice were depending on different, mostly unknown circumstances. Similar effects were observed when preliminarily measuring the resistivity of snow and ice. Therefore, it seemed to be of importance to carry out the present measurements under conditions as clearly defined as possible. The first task was to get the substance to be investigated—ice—prepared under such conditions. It seemed that single ice crystals would be best for this purpose, and therefore it was attempted to grow these. However, it should be noted already here that even under the best conditions one cannot expect the values of the measured resistivity of ice to be definite and reproducible because ice, when conducting electricity, is not like a metallic conductor with definite properties. The electrical properties of all the substances with non-metallic properties for conduction of electricity depend on different circumstances, even on impurities in small quantities added to the basic substance, and to eliminate all the troublesome circumstances seems to be a task which cannot be solved easily.

2. The growing of single ice crystals, their treatment and optical testing

Several methods for growing single ice crystals are described in the literature. Adams and Lewis [1] have used a method by which crystals up to 10 cm have been grown. As far as we know, growing with this method has not been repeated. References to two other methods used are given by Jona and Scherrer [11]. The second of these methods is that known as the Kyropoulos method [14, 15]. By this method very good reproducible results may be obtained, but, as noted by Jona and Scherrer [11], a long time (6 days) is necessary for obtaining sufficiently large ice crystals. Therefore, it seemed to us that the first method used by Jona and Scherrer might be more acceptable. This method is based on the observation that in nature on the surface of still water. e.g. in ponds, ice is formed with its singular axis orientated vertically. This observation dates back to Brewster [4]. As indicated by ESKOLA [6], the ice cover of an entire sea may be constituted of only one single ice crystal. Trey [20] describes such a single-crystal cover of ice (called "blue ice" on the Åland islands in the Baltic between Sweden and Finland, as noted by him) observed in the Gulf of Riga in the Baltic. After Trey "the weather conditions for forming a blue-ice cover are marked by a high-pressure region. Such lasting high-pressure regions were observed in the northern areas at the end of winter: then absolute calm and cloudless sky are present there and thus considerable irradiation is caused during the night. The cooling down follows for the most part by irradiation and is very evenly distributed over large areas." The conditions for the formation of such an ice cover are described by Jona and Scherrer [11] as follows: "During this natural formation [of the ice cover in question] the water surface is in contact with the air cooled down considerably below 0°. Then layers of water will be formed with temperature and density increasing downwardly. When the temperature gradually decreases the pure water freezes from the surface downwardly and the layers of water are not displaced. It is of importance that the cooling down takes place very slowly so that a crystal-like arrangement of water molecules appears extending possibly deep into the water itself already before the formation of ice and especially when the surface of the water is quiet."

Jona and Scherrer have attempted to produce such conditions with their "Method of slowly cooling down with a parallelly directed temperature gradient". With some modifications, this method was used by us for growing ice crystals.

2.1. *Arrangement used for growing single ice crystals.*—The room where ice crystals were grown was a cold-box (Fig. 1) with a volume of 185 litres and the lowest temperature reached there was $-25°$ to $-27°$C.

The proper arrangement for growing ice crystals was as follows. A cylindric vessel of tinned sheet iron with a diameter of 9 cm and a height of 12 cm was used for cooling the water. Oxidized

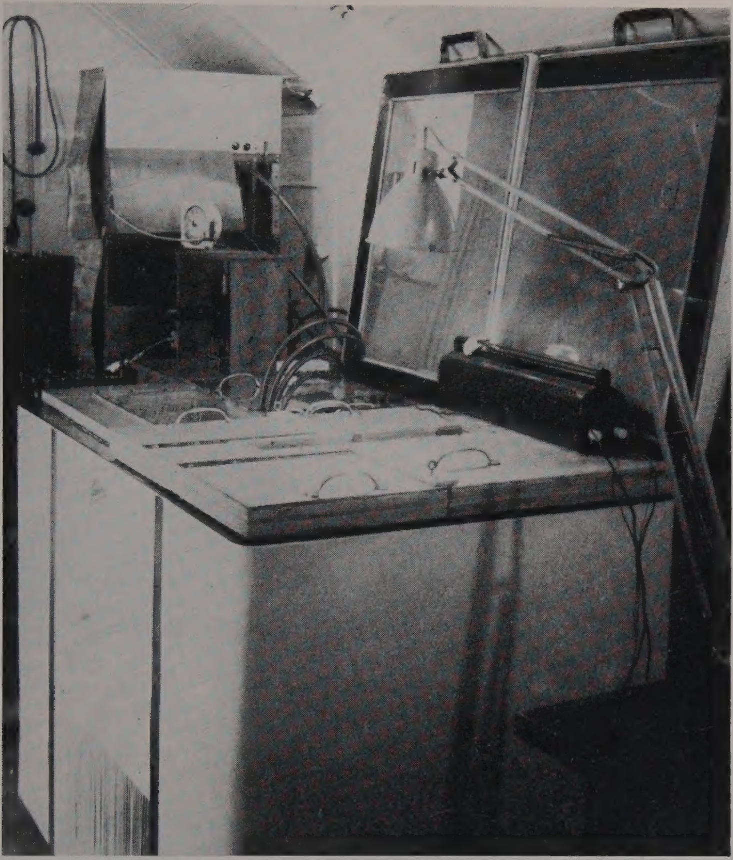


Fig. 1. The cold-box used.

constantan wire of 0.3 mm was compactly wound around the vessel in three separate sections with equal resistances (Fig. 2). The vessel was embededd in a larger cardboard box and thermically insulated with glass-wool. All the three resistances were connected in parallel to the net. The temperature in the cold-box where the vessel was placed was maintained at $-20°C$. By regulating the current through the resistance sections it was possible to adjust the temperature in the water to be cooled so that on the surface there were 0° or a little above, and downwards a higher temperature up to 1–2°C. With such a temperature distribution in the water it might be expected that (1) the crystal-like arrangement of the water molecules was possibly obtained near the water surface already before freezing, and (2) impurities solved in the water could be displaced down from the cooling surface because of their higher density. If the cooling took place slowly it could be expected that these processes would be more pronounced. More details on the mechanism of the processes considered and on the technical procedure may be found in the original paper by Jona and Scherrer [11]. Round pieces of ice with a diameter of 7–8 cm and a height of 5–6 cm were obtained with the arrangement described. They were examined first optically and then treated mechanically for obtaining the geometrical shape desired with the devices described below.

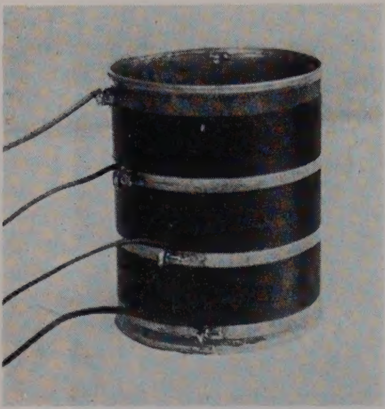


Fig. 2. The vessel for growing the ice crystals.

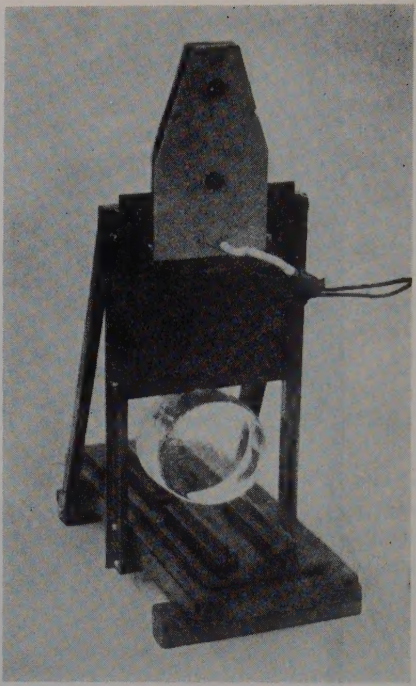


Fig. 3. Device for cutting ice pieces.

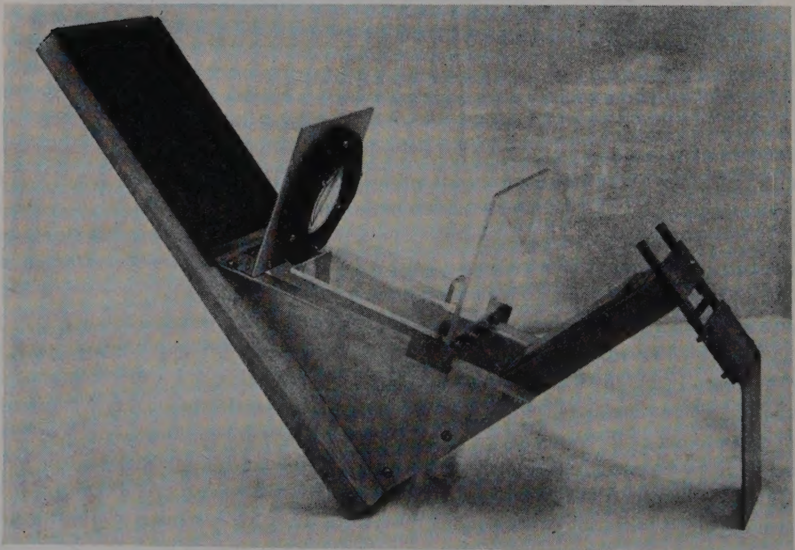


Fig. 4. Polariscope for optical testing of the ice crystals.

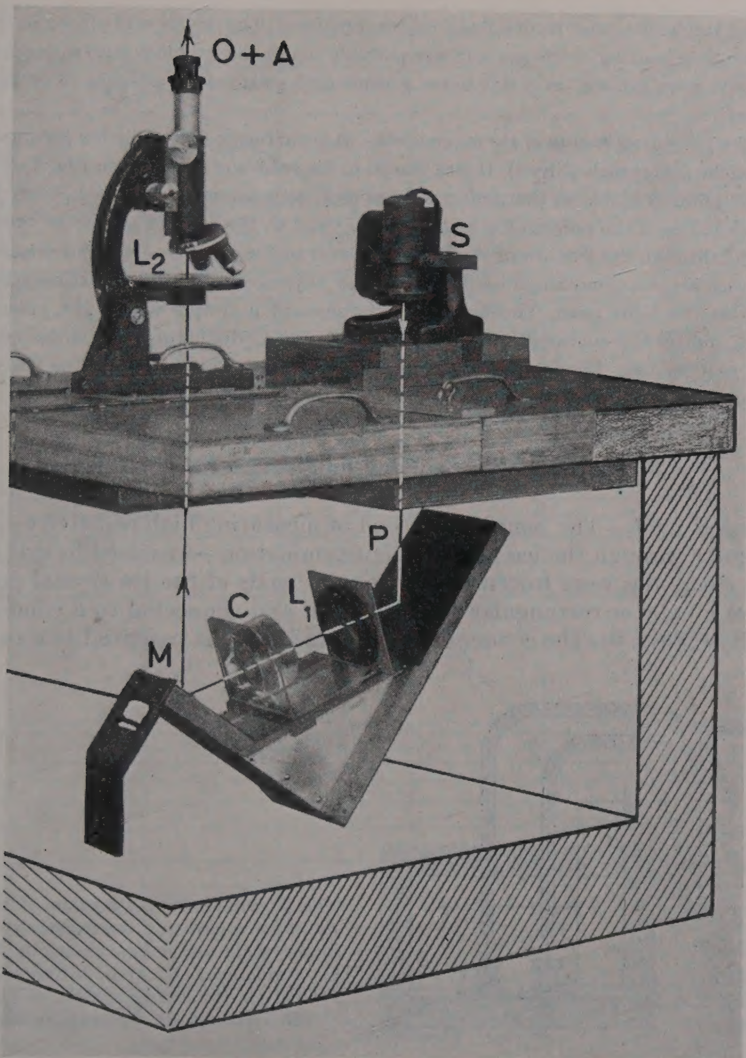


Fig. 5. Arrangement of the polariscope in the cold-box.

2.2. *Cold-box.*—The cold-box was used for growing the ice pieces, for their treatment and also for maintaining the ice crystals finished for the electrical measurements at the desired temperature. It was manufactured by Graham Brothers, U.S.A., with a volume of 185 litres (width 51 × 98 cm^2, height 37 cm). The lowest temperature of -25 to -27°C was reached in the cold-box after 2 hours starting from room temperature. For having possibilities to observe events in the cold-box and for necessary manipulating in it the hoods of the cold-box were opened and replaced by two thick covers constructed of paste-board with double windows of plexiglass and with hatches for hands, arranged as shown in Fig. 1.

2.3. *Geometrical forming of the ice pieces.*—For the desirable geometrical forming of the ice pieces a guillotine-like device with a 1 mm thick brass knife was constructed (Fig. 3). On the top of the knife a 100 watt heater from a flat-iron was arranged. The device was placed in the cold-box and by reasonable heating of the knife it was possible to cut the ice block into appropriate pieces. The pieces cut were ground on a flat brass surface and polished by putting filter paper on the brass surface.

2.4. *Device for optical testing of the ice crystals.*—A polariscope was built for testing the optical properties of the ice crystals (Fig. 4). It was placed in the cold-box as shown in Fig. 5. A 13 × 18 cm glass plate P painted black on the underside was used as polarizator. A lens L_1 with $F_1 = 27$ cm was inserted between the polarizator and the ice crystal C. By a silver mirror M the light beam was reflected through the window of the cold-box cover to the analyser—a Nicol prism—arranged on the 4 × ocular of a microscope used without the objective and after inserting a lens L_2 with $F_2 = 12$ cm in the light path. Through this arrangement a simple wide-sight polariscope was constructed, and by the coloured images seen it was easy to distinguish the single crystals from the mosaic polycrystals. Likewise in a simple way it was possible to determine the orientation of the singular axis.

3. Discharge of a condenser through ice crystals

3.1. *Method used.*—The simplest method of measuring high resistivity—discharge of a condenser through the ice piece under examination—was used in this investigation. Two electrodes were frozen to the opposite ends of the ice crystal prepared in the form of a cube or rectangular parallelepiped and connected to a condenser with the capacity C (Fig. 6). The condenser was charged and its potential U was measured

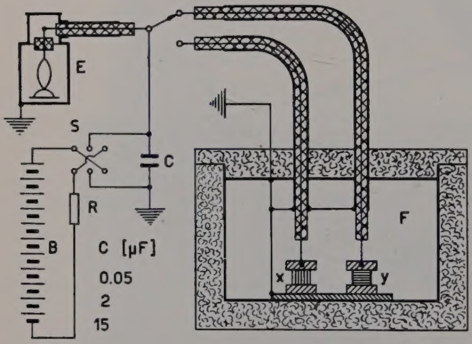


Fig. 6. Schematical diagram of the arrangement for measuring the resistivity of ice. x, y, ice crystals under examination; F, cold-box; C, condenser; E, Wulf bifilar electrometer; S, switch for commutation of the polarity; B, battery; R, protection resistance.

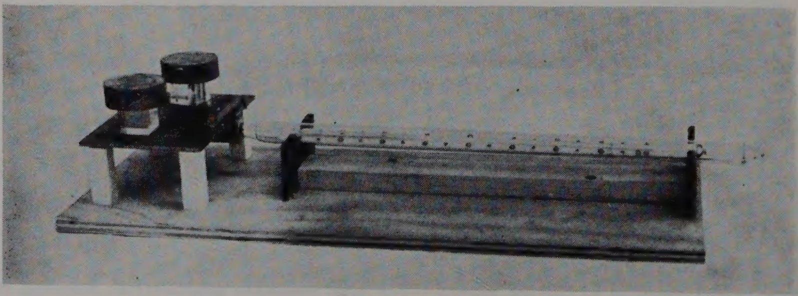


Fig. 7. Arrangement of the crystals on a stage with thermometer.

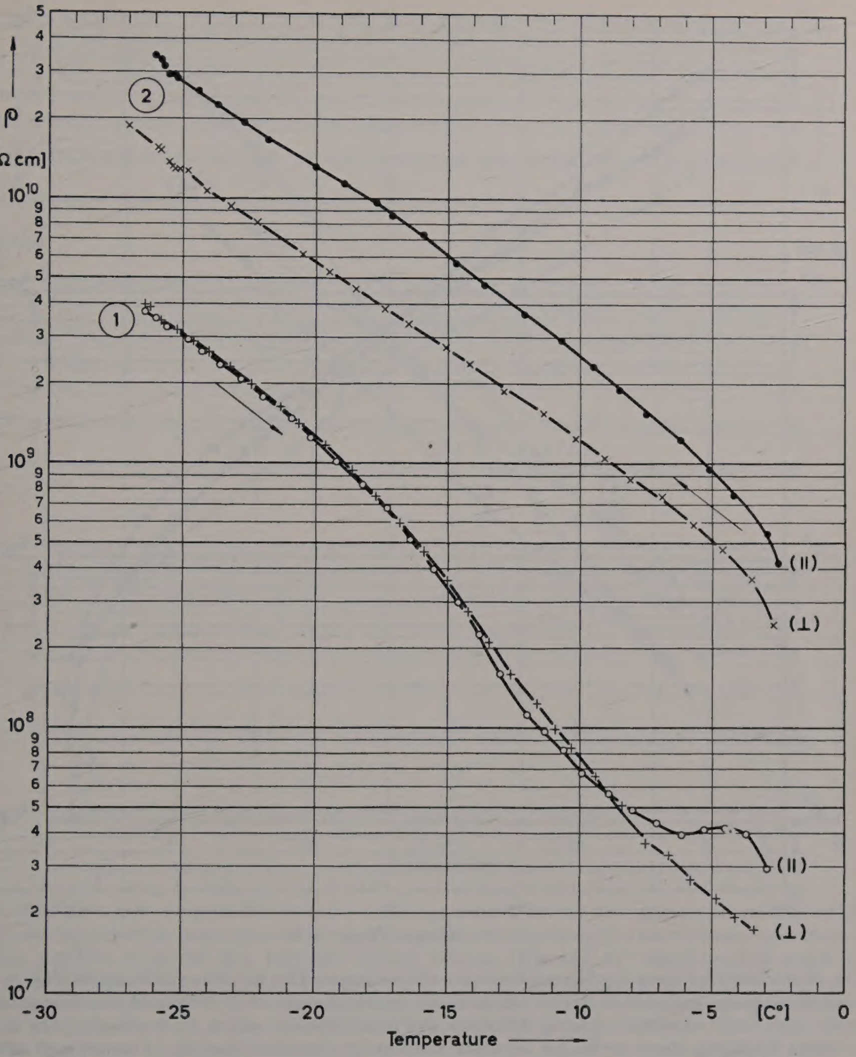


Fig. 8. Resistivity of ice ϱ in dependence on temperature. Before the measurements the cold-box was adjusted at the lowest possible temperature ($-27°$C) and the upper electrodes of the ice crystals were connected with the negative terminal of a 135-volt battery during 16 hours. (1) measurement series by increasing the temperature: up to $-15°$C resistivity of both the crystals was equal, thereupon it was different. After finishing this series ice crystals were under tension (135 V) during 18 hours and after that (2) measurement series were carried out by decreasing the temperature. Note: (1) increase of the resistivity caused by the tension during the pause, and (2) difference between (⊥) and (||) during this series.

with a Wulf bifilar electrometer connected to the terminals of the condenser and the ice crystal respectively. By discharging through the ice at a time instant t the potential is

$$U_t = U_0 e^{-\frac{t}{RC}}$$

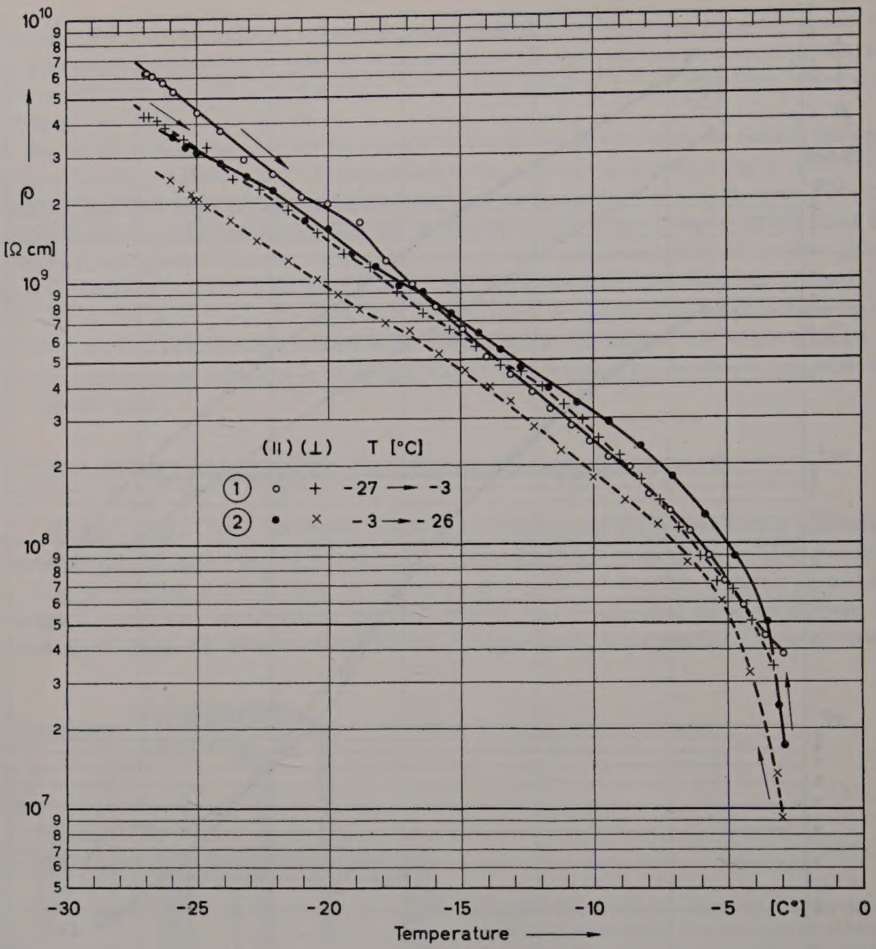


Fig. 9. Resistivity of ice ϱ in dependence on temperature. The same crystals as in Fig. 8. Before the measurements the cold-box was adjusted at a temperature of -27°C and the electrodes of ice crystals were short-circuited during 24 hours. (1) measurement series by increasing the temperature. After finishing these series ice crystals were short-circuited during 18 hours and after that (2) measurement series were carried out by decreasing the temperature.

where U_0 is the initial potential at $t = 0$ and R is the resistance of the ice crystal used if the insulation of the entire system is so high that the leakage current can be neglected, as it was in our case where the condensers and screened connection cables were of very high quality. The resistance of the ice piece under examination is then

$$R = \frac{1}{C} \cdot \frac{t}{\ln (U_0/U_t)}.$$

Condensers with different dielectrics were examined and the following found to be the best:

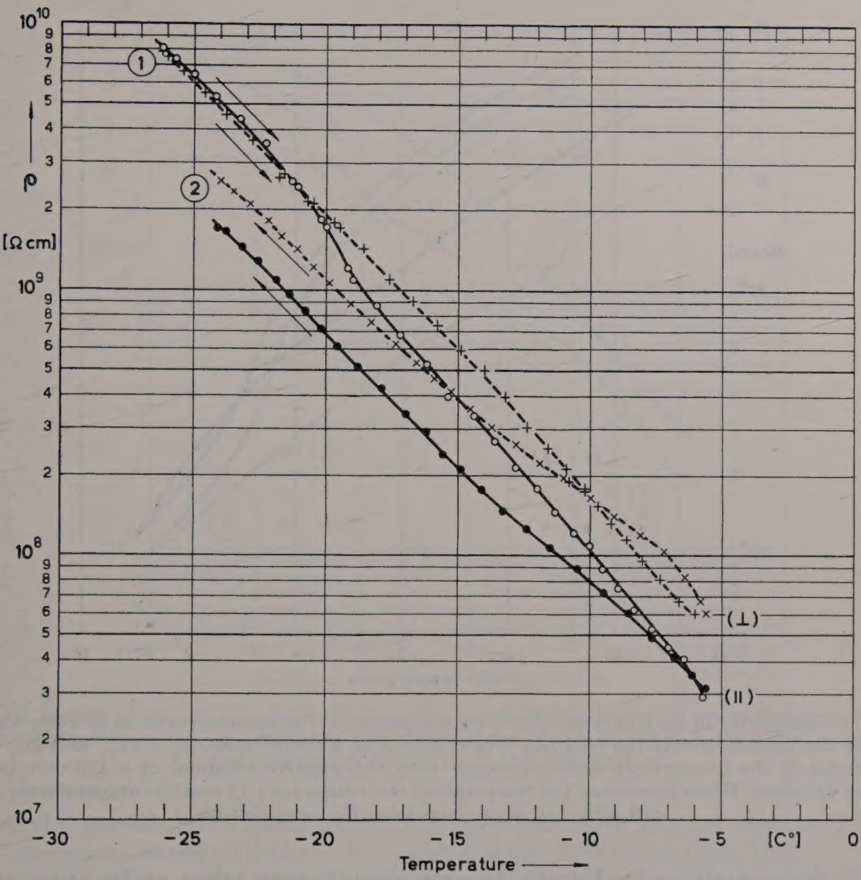


Fig. 10. Resistivity of ice ϱ in dependence on temperature. Before the measurements the cold-box was adjusted at a temperature of −26°C, and the upper electrodes of the ice crystals were connected with the positive terminal of a 140-volt battery during 16 hours. (1) measurement series by increasing the temperature. (2) measurement series without interruption after the first series by decreasing the temperature. Note: equal values for (⊥) and (||) at the beginning of the first series and the difference later.

			Leakage resistance
0.05 μF	16 000 VDC	Vitamin Q	$6 \times 10^{11}\ \Omega$
2 μF	1 000 VDC	Nitrogol	$1.1\text{–}2.7 \times 10^{10}\ \Omega$
3 μF	330 VAC	Pyranol	$9\text{–}9.6 \times 10^{9}\ \Omega$

In some cases five of the last-mentioned 3 μF condensers were connected in parallel and used as a condenser with a capacity of 15 μF. No polarization effects were observed by charging and discharging the condensers.

The ice piece under examination was placed in the cold-box and its electrodes were connected to the condenser and electrometer by the aid of high quality screened cables.

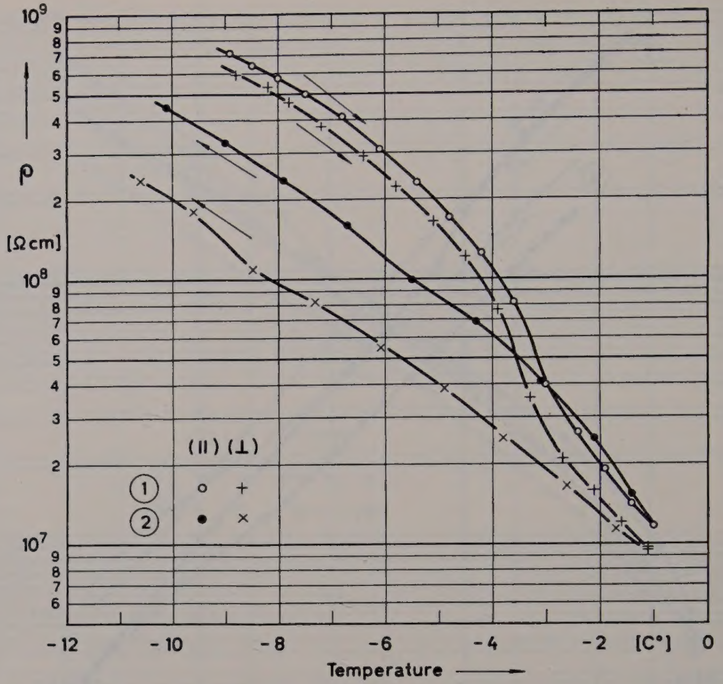


Fig. 11. Resistivity of ice ϱ in dependence on temperature. The same crystals as in Figs. 8 and 9. Before the measurements the cold-box was adjusted at a temperature of −11°C and the upper electrodes of the ice crystals were connected with the positive terminal of a 135-volt battery during 45 hours. When increasing the temperature the values for (⊥) and (||) comparatively equal, and different when decreasing the temperature.

3.2. *Ice crystals used.*—Usually two ice crystals were taken under examination, one with electrodes for the field || to the optical axis and the second ⊥ to the optical axis. The base surface of the crystals was 2.5–2 cm in square and their height was 2.5–1.5 cm. The arrangement of the crystals on a stage with thermometer is shown in Fig. 7. A brass plate was used as the grounded electrode for both crystals, and the cylindric brass caps served as the insulated electrode. The crystals were frozen to the electrodes.

3.3. *Resistivity—temperature function.*—Variation with temperature of the resistivity of ice computed from the measurements is shown in Figs. 8 and 9 for the same two crystals and in Fig. 10 for two other crystals. In the temperature interval −27→ −2°C and vice versa the resistivity varied nearly by three powers; however, the tendency of the variation was different even for the same crystals (Figs. 8 and 9). A detailed description of the conditions before and during the measurements is given in the text to the figures. One property shown in the figures can be noted. If at a low temperature an electric field was applied to the crystals during a certain period of time, the values for the resistivity of both crystals (⊥ and ||) were practically equal (Figs. 8 and 10), while they differed with increasing temperature, and with subsequently decreasing temperature this difference increased. The same trend is shown in Fig. 11 when the starting temperature was higher (−9°C). After a 2 hours' pause during

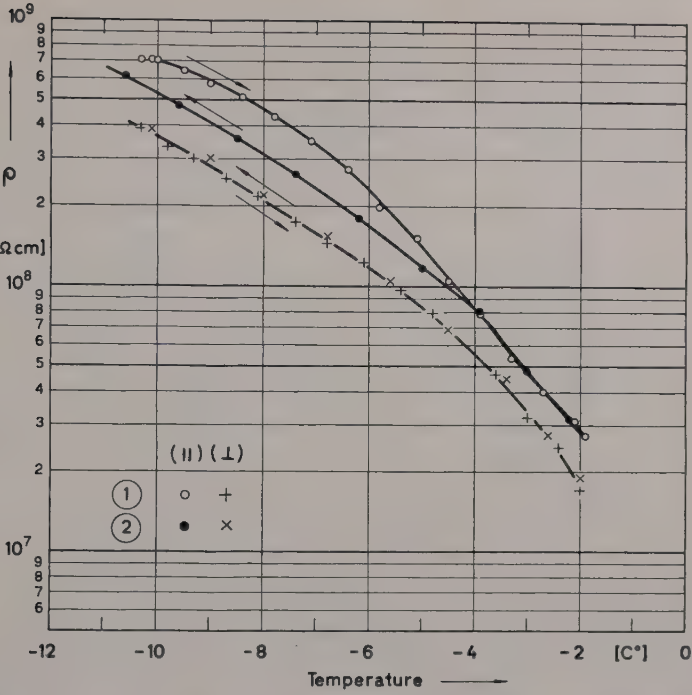
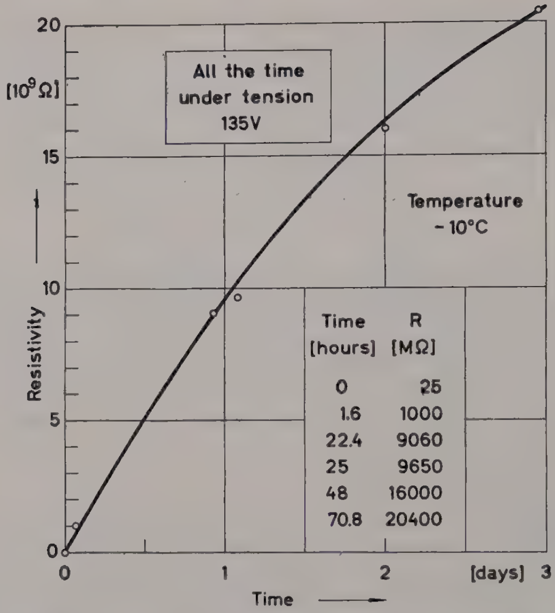


Fig. 12. Resistivity of ice ϱ in dependence on temperature. Repetition of series shown in Fig. 11 after 2 hours' pause during which the upper electrodes of the ice crystals were connected with the positive terminal of a 135-volt battery.

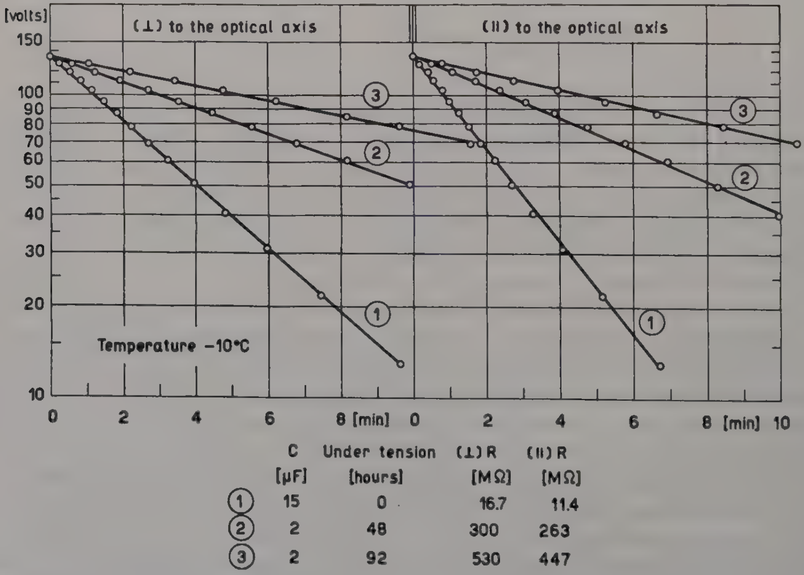
which the crystals were under tension, the previous state was not reached (Fig. 12) and the curves obtained differed from those of the first series (Fig. 11).

3.4. *Dependence of the resistivity on the preceding treatment.*—The facts considered seem to evince that the resisitivity of ice for the most part depends on the preceding treatment of the ice piece under examination. The principal controlling factors might be three—the temperature, the electrical field applied, and the time during which it is applied. No definite evidence was obtained regarding the temperature. The influence of the electrical field considered in the previous section is clearly shown in Fig. 13. The ice crystal was under tension during 3 days and its resistance gradually increased more than 800 times. Similar variations are shown in another form in Fig. 14 where the dropping of the potential of the condenser connected with the ice crystal is shown in a logarithmic scale when the electric field was applied during a certain period of time. The dropping is represented by straight lines and from their inclination the resistivity was computed. The potential applied to the ice crystal decreased with time when measuring the resistivity by discharging the condenser. Therefore, it was attempted to measure the resistivity also by using the potential divider method shown schematically in Fig. 15. This method also shows that the resistivity increased with time when the crystal was under tension. As already mentioned, when considering the discharge of the condenser through ice, the potential dropping curves were straight lines in a logarithmic scale (Fig. 14), and therefore it was possible to compute the ice resistivity from their inclination.



Time [hours]	R [MΩ]
0	25
1.6	1000
22.4	9060
25	9650
48	16000
70.8	20400

Fig. 13. Increase of the resistivity of an ice crystal with time when it was all the time under tension of 135 volts.



	C [µF]	Under tension [hours]	(⊥) R [MΩ]	(‖) R [MΩ]
①	15	0	16.7	11.4
②	2	48	300	263
③	2	92	530	447

Fig. 14. Potential dropping of a condenser connected with an ice crystal in dependence on the time during which a constant forming potential was applied.

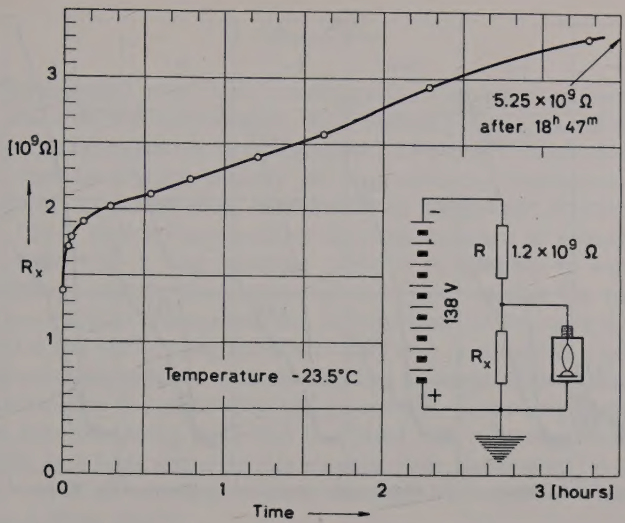


Fig. 15. Increase of the resistivity of ice with time during which a constant potential was applied. Measurements carried out by potential divider method.

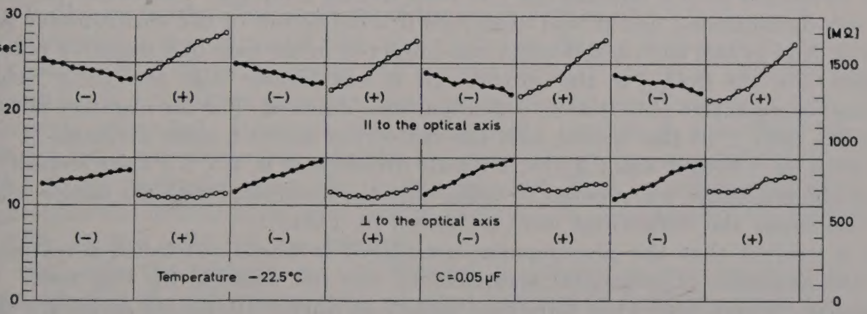


Fig. 16. Variation of the time for discharge of a condenser through ice crystals from a potential of 135 volts to 90 volts by alternation of the field polarity. On the right-hand side, scale for resistivity, assuming its alternation with time.

Such were the conditions in all the cases considered above. However, in some cases this was not so, as shown for instance in Fig. 16 by curves representing time intervals during which a condenser was discharged through ice crystals from a potential of 135 volts to 95 volts. The time intervals changed with time and differently in dependence on the polarity of the electrical field applied. The different tendency of the curves of $(\parallel)$ and $(\perp)$ field is also worth noting. If the observed phenomenon could only be caused by variation of the resistivity, the resistivity should be computed by using the time intervals measured. Such computation was carried out and the values obtained can be determined by using the scale on the right-hand side of the figure. However, it seems that the phenomenon observed was not caused solely by variation of the resistivity. After finishing the measurement series the following preliminary experiment was carried out. The condenser of 0.05 μF capacity and the ice crystal

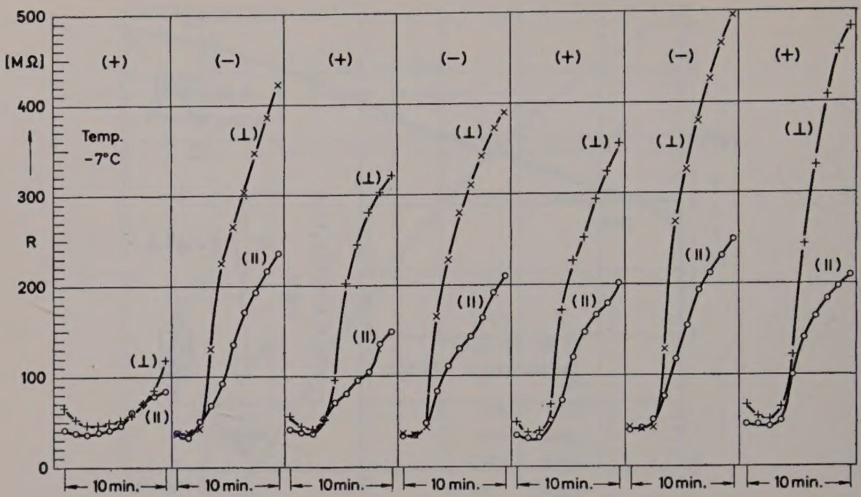


Fig. 17. Short-time variations of the resistivity of ice when alternating the polarity of the potential applied.

were connected with a potential of 135 volts during 1 minute. Thereafter the potential was disconnected and it was examined if a deflection of the electrometer would appear. And in fact such a deflection was observed in the case of a negative potential applied. For the field || to the optical axis it was greater than for the ⊥ field. In the case of a positive potential no deflection was observed. For the negative potential with the field ⊥ to the optical axis the deflection was 0.1 scale divisions (1 volt), and with the || field it was 1.3, 0.8, 1.1 scale divisions or 6, 4.5, 5.5 volts respectively. When the procedure was repeted by using only the ice crystal with the cables without the condenser the deflections were as shown in Table 1.

It is evident that the phenomenon considered is worth a detailed investigation, but the available experimental arrangement was not suitable for this task.

Similar, though somewhat different, variations during 10-minute series are shown in Fig. 17. These variations, too, must be investigated in greater detail and by suitable means.

Table 1. Deflection of electrometer after forming of an ice crystal with electric field.

Time [min.]	Ice crystal with electric field ⊥ to optical axis			Ice crystal with electric field || to optical axis		
	Polarity	Scale divisions	[Volts]	Polarity	Scale divisions	[Volts]
29	(+)	0.5	3.5	(−)	10	22
30	(−)	0.7	4.2	(+)	0	0
31	(+)	0.7	4.2	(−)	7.5	18
32	(−)	1.5	6.7	(+)	0	0
33	(+)	1.7	7.3	(−)	10.0	22

4. Discussion

As shown by the material presented, investigation of the electrical resistivity of ice is connected with some difficulties because the resistivity changed considerably under different, not always controllable circumstances. As already mentioned in the introduction, this is not surprising because all non-metallic conductors have similar properties. Therefore, as a first step, it might be of advantage if it would be possible to treat the ice block under examination in some manner to remove its previous history. For crystals with a high melting point it is possible to carry out such a treatment by heating, and by the increased molecular motion the inner properties formed during the previous treatments can be removed. In the case of ice, the highest usable temperature for performing such an operation is somewhat below zero, and, as shown, no effect of importance was obtained at a temperature some degrees below zero. As the next means for removing the properties formed by the previous treatments, handling by alternating potential was tried. No influence resulted from preliminary attempts, but later experiments showed that there may be some prospects in the treatment with alternating current through ice crystals. This problem will be considered in a later paper.

During the present investigation no means were found to remove the properties formed by the previous handling. Further, as shown by the present measurements, the resistivity of ice increased considerably when a unipolar electric field was applied to the ice crystal. This increase of the resistivity could be explained by asuming that something was removed from the crystal or at least displaced in it, and for the investigation of these processes the current through ice must be investigated by measuring it with direct methods. Another conclusion could also be drawn from the material presented. It seems that under some conditions something can be introduced from the electrodes into the ice piece. Therefore, the influence of the material of the electrodes must also be investigated. That something happened at the electrodes was indicated by some change observed on the surface of the electrodes where the contact with ice was present.

Nor can, with the material at our disposal, a definite answer be given to the question whether the difference observed when the electric field was applied $\perp$ or $\parallel$ to the optical axis was in fact caused by the different orientation of the crystal lattice. This question deserves to be investigated from other points of view. Such are the ways for a further extension of the investigation of the elementary electrical properties of ice, and by solving these problems it may be expected that some phenomena considered here will also be clarified.

ACKNOWLEDGEMENTS

The author is grateful to the Director of the Institute of High Tension Research of the University of Uppsala, Professor H. Norinder, for providing him with facilities to carry out this work and for his interest in its progress. Thanks are due to the Swedish Natural Science Research Council for placing means at the disposal of the Institute to perform this investigation. The author gratefully acknowledges the assistance of Mr. A. Metnieks.

Institute of High Tension Research, University of Uppsala, August 1956.

REFERENCES

1. Adams, J. M., and Lewis, W., The production of large single crystals of ice. *Rev. Sci. Instr., 5*, 400–402 (1934).
2. Ayrton, M. F., and Perry, *Proc. London Phys. Soc., 2*, 178 (1877), cited from [10].
3. Bandel, H. W., Corona from ice points. *J. Appl. Phys., 22*, 984–985 (1951).
4. Brewster, D., *Phil. Mag.* (3), *4*, 245 (1834), cited from [1].
5. Brommels, H., Bestimmung der Dielektrizitätskonstante und des elektrischen Leitungsvermögens des Eises. *Societas Scientiarum Fennica, Commentationes Physico-Matematicae*, I, *19*, 1–5 (1922).
6. Eskola, P., *Kristalle und Gesteine*, S. 323, Wien: 1946. Springer-Verlag.
7. Gränicher, H., Scherrer, P., and Steinemann, A., Erhöhung der Dielektrizitätskonstanten des Eises durch Halogeneinlagerung. *Helv. Phys. Acta, 27*, 217–219 (1954).
8. Gränicher, H., Jaccard, C., Scherrer, P., and Steinemann, A., Dielektrische Eigenschaften des Eises bei sehr tiefen Frequenzen und der Einfluss eines Vorfeldes. *Helv. Phys. Acta, 28*, 300–303 (1955).
9. Humbel, F., Jona, F., and Scherrer, P., Anistotropie der Dielektrizitätskonstante des Eises. *Helv. Phys. Acta, 26*, 17–32 (1953).
10. Johnstone, J. H. L., The electrical resistance and temperature coefficient of ice. *Proc. Trans. Nova Scotian Inst. Science* (Halifax), *13*, 126–144 (1912).
11. Jona, F., and Scherrer, P., Die elastische Konstanten von Eis-Einkristallen. *Helv. Phys. Acta, 25*, 35–37 (1952).
12. Koenig, H., Elektroneninterferenzen an Eis. *Nachr. Akad. Wissensch.* (Göttingen), Math. Phys. Kl., 1–6 (1942).
13. —— Eine kubische Eismodifikation. *Z. Krist.* (A), *105*, 279–286 (1943).
14. Kyropoulos, S., *Z. anorg. Chem., 154*, 308 (1926).
15. —— Dielektrizitätskonstanten regulärer Kristalle. *Z. Phys., 63*, 849–854 (1930).
16. Lisgarten, N. D., and Blackman, M., The cubic form of ice. *Nature, 178*, 39–40 (1956).
17. Norinder, H., and Siksna, R., On the electrification of snow. *Tellus, 5*, 260–268 (1953).
18. —— Experiments concerning electrification of snow. *Ark. geofysik, 2*, Nr 3, 59–89 (1954).
19. —— Electric charges measured in the air when blowing snow. *Ark. geofysik, 2*, Nr 14, 343–369 (1955).
20. Trey, F., Über die grösste Einkristallbildung. *Berg- und hüttenmännische Monatshefte, 94*, 101-104 (1949).

Tryckt den 15 mars 1957

Uppsala 1957. Almqvist & Wiksells Boktryckeri AB